

CAE 208 / MMAE 320: Thermodynamics

Fall 2023

November 07, 2023
Intro to second law (2)

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Dr. Mohammad Heidarinejad, Ph.D., P.E.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology

muh182@iit.edu

ANNOUNCEMENTS

Announcements



Architectural Engineering Panel

ASCE and ASHRA Co-Event: Panel to
discuss many AE topics not covered at IIT

RE 104 | Wednesday 11-8
During Lunch | Food Will be Provided



Announcements

- The solution to Assignment 7 is posted
- Assignment 8 is posted
- Midterm exam 2 is this coming Thursday
- All students are responsible for their open book exam part
 - No book / tables sharing will be allowed
 - I will not bring any extra books

Announcements

- Watch the recordings if you need additional review time

- CAE_208_MMAE_320.2024 10 (Thermodynamics)
- Home
- Syllabus
- Content
- Assignments
- Discussions
- Collaborate Ultra
- Class Recording | Panopto
- My Grades
- Email
- Galvin Library
- Tools

Panopto Content

Search in folder "CAE_208_MMAE_320.202410: Thermodynamics"...


+ Create

CAE_208_MMAE_320.202410: Thermodynamics

Sort by: Name Duration Date Rating

+ Add folder

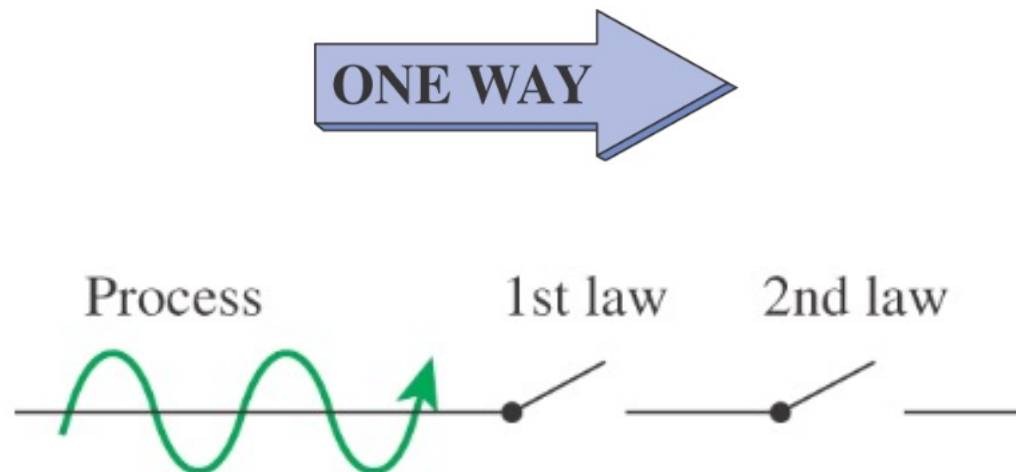
10/05/2023 Lecture14_Energy analysis of closed systems (2)



RECAP

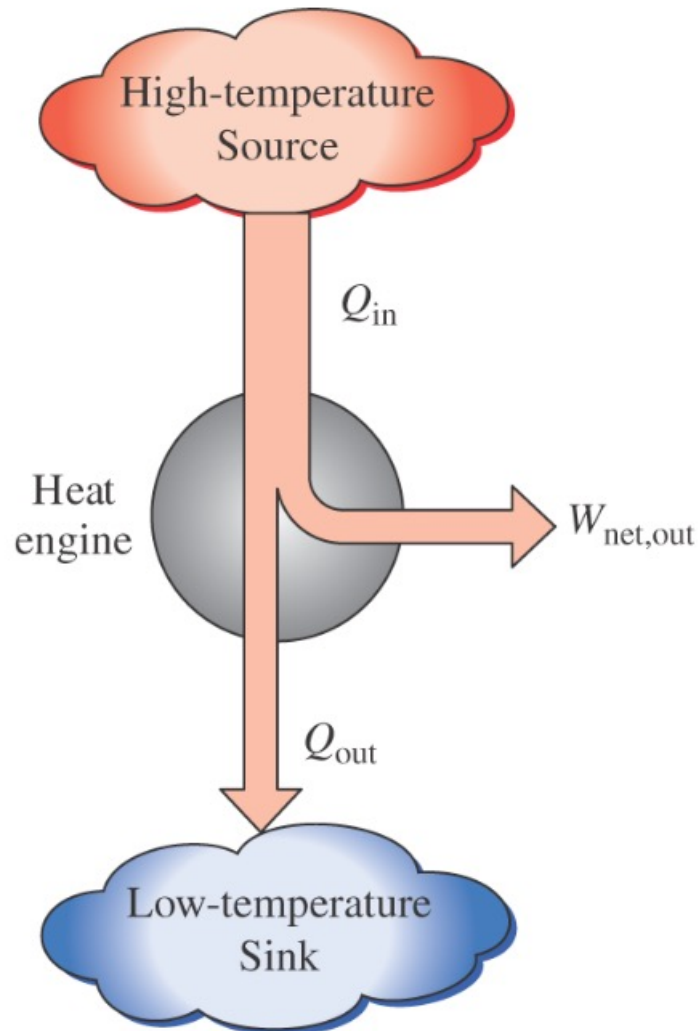
Recap

- It is clear from these arguments that processes proceed in a certain direction and in the reverse direction
- The first law places no restriction on the direction of a process but satisfying the first law does not ensure that the process can actually occur



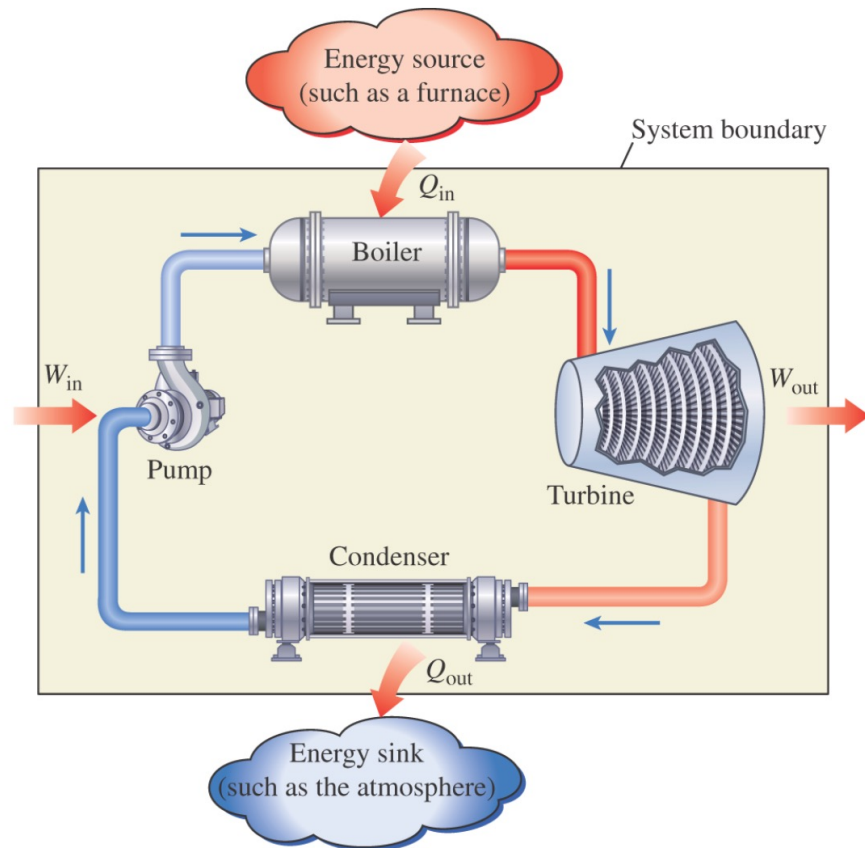
Recap

- Heat engines cycles are as following:



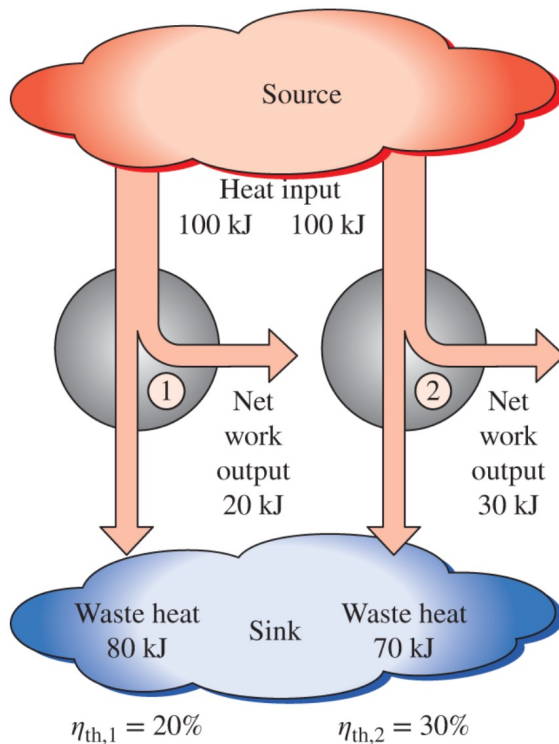
Recap

- The best example of a heat engine is the steam power plant:



Recap

- The fraction of the heat input that is converted to net work output is a measure of the performance of a heat engine is called the *thermal efficiency*



$$\text{Thermal efficiency} = \frac{\text{Net works output}}{\text{Total heat input}}$$

Recap

- The Second Law of Thermodynamics: Kelvin-Planck Statement:

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work

No heat engine can have a thermal efficiency of 100 percent

For a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace

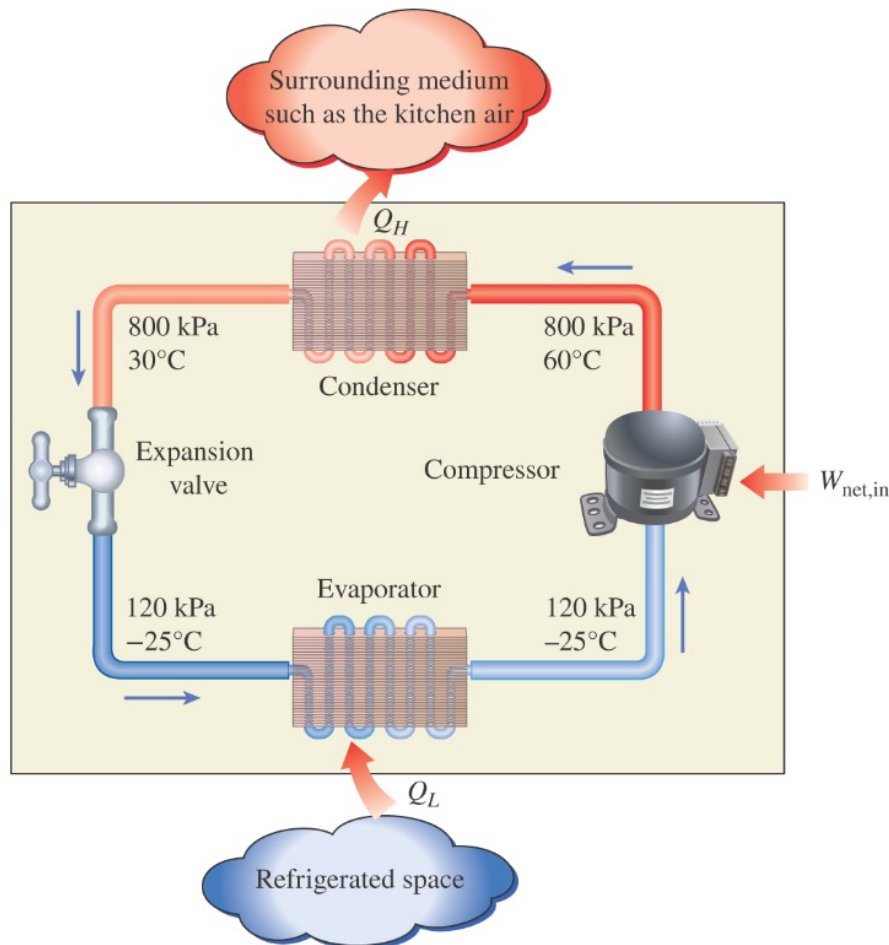
REFRIGERATORS AND HEAT PUMPS

Refrigerators and Heat Pumps

- ***Refrigerators:*** The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called **refrigerators**
- Refrigerators, like heat engines, are cyclic devices
- The working fluid used in the refrigeration cycle is called a **refrigerant**

Refrigerators and Heat Pumps

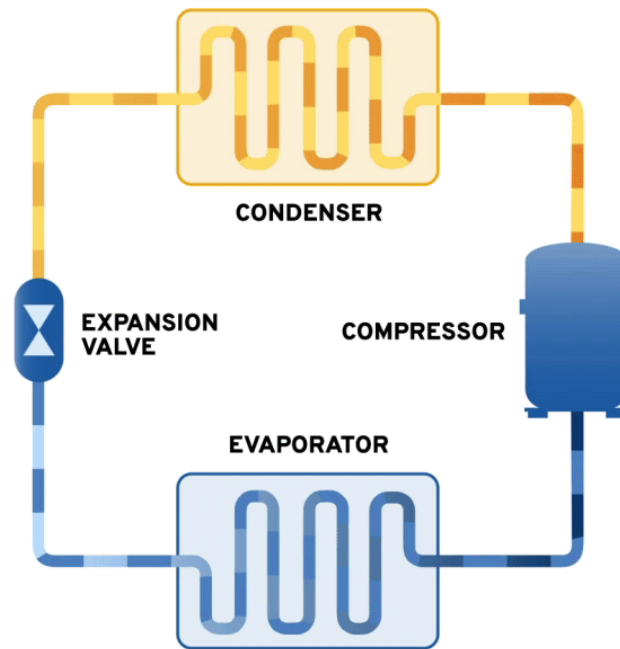
- The most frequently used refrigeration cycle is the **vapor-compression refrigeration cycle**



Refrigerators and Heat Pumps

- The most frequently used refrigeration cycle is the **vapor-compression refrigeration cycle**

Refrigeration Cycle



froztec.

Refrigerators and Heat Pumps

- How many of you have seen the back of old refrigerators:



Refrigerators and Heat Pumps

- Side note: Are there any throttling valves around us in our campus?



Refrigerators and Heat Pumps

- The efficiency of a refrigerator is expressed in terms of the coefficient of performance (COP)
- The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space

Refrigerators and Heat Pumps

- COP of refrigeration is expressed as:

$$COP_R = \frac{\text{Desired output}}{\text{Require input}} = \frac{Q_L}{W_{net,in}}$$

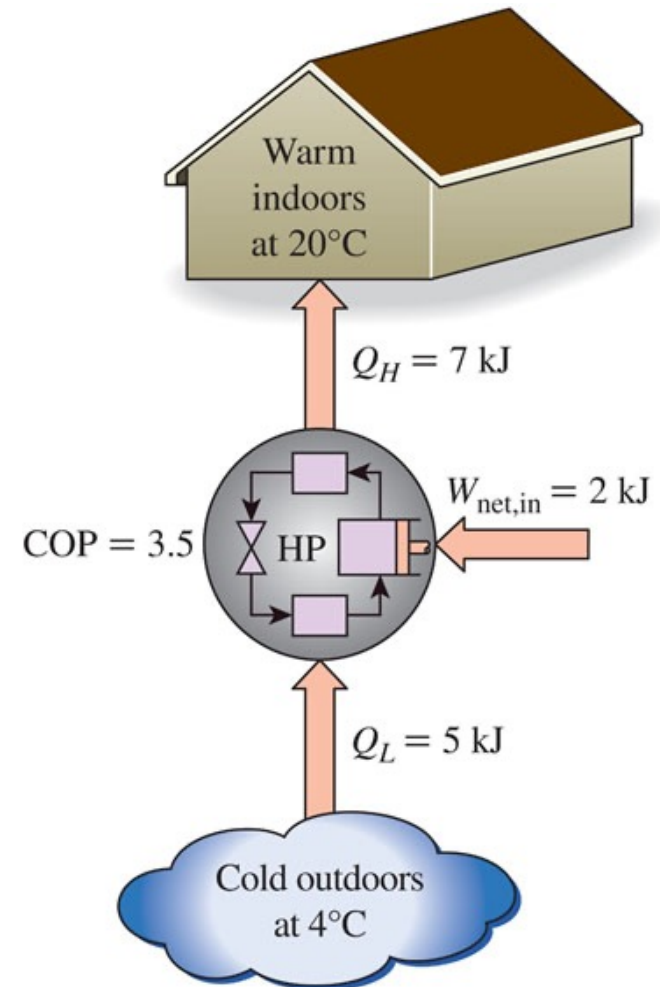
$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

Refrigerators and Heat Pumps

- Can the value of COP_R be greater than unity?

Refrigerators and Heat Pumps

- **Heat Pumps:** The objective of a heat pump is to maintain a heated space at high temperature. This is accomplished by absorbing heat from a low-temperature source, such as well water or cold outside air in winter and supplying this heat to the high-temperature medium as a house:



Refrigerators and Heat Pumps

- *Heat pumps* are in the news right now:



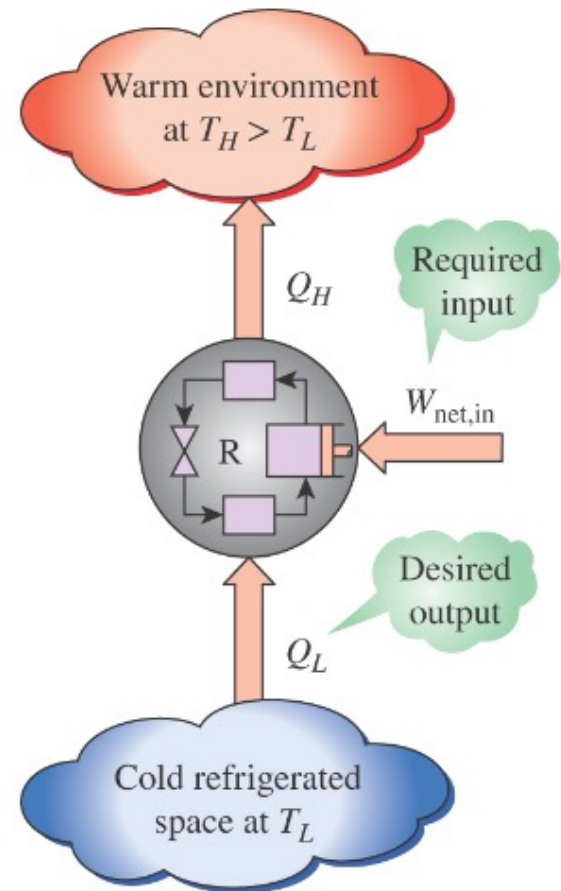
- **Heat Pumps** — Our nation's buildings, homes, offices, schools, hospitals, military bases, and other critical facilities drive more than 40% of all U.S. energy consumption. To reduce the amount of energy needed in our buildings, leading to less reliance by the U.S. and allies on adversaries such as Russia for oil and gas, heat pumps are an important solution. Their use by the U.S. and allies can shrink Russian revenue for war and reduce climate instability. However, currently, U.S. HVAC manufacturers are not producing heat pumps at the rate needed. The Biden-Harris Administration can help American manufacturing expand and expedite the installation of heat pumps in homes and residential buildings by qualified building professionals.

Refrigerators and Heat Pumps

- **Heat Pumps:** The objective of a heat pump is to supply heat Q_H into the warmer space

$$COP_{HP} = \frac{\text{Desired output}}{\text{Require input}} = \frac{Q_H}{W_{net,in}}$$

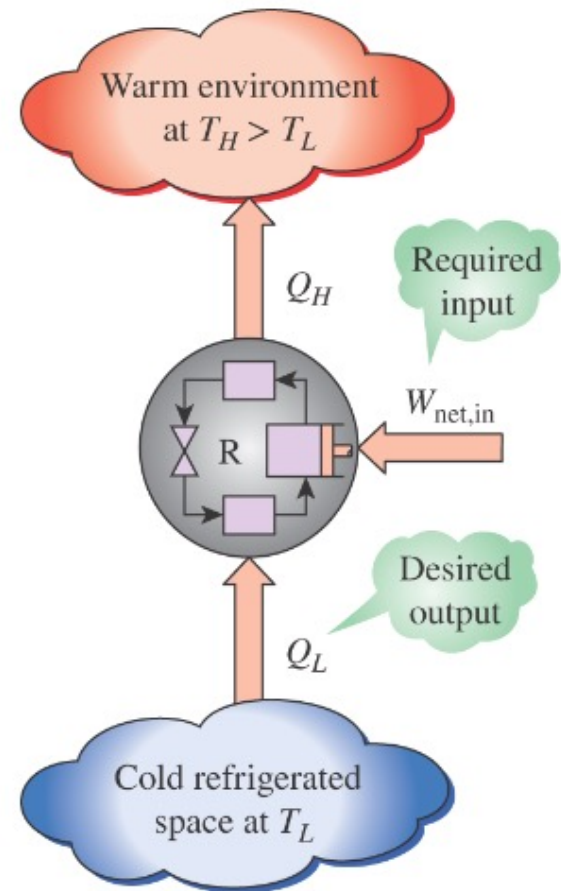
$$COP_{HP} = \frac{\text{Desired output}}{\text{Require input}} = \frac{Q_H}{Q_H - Q_L}$$



Refrigerators and Heat Pumps

- **Heat Pumps:** The objective of a heat pump is to supply heat Q_H into the warmer space

$$COP_{HP} = COP_R + 1$$



Refrigerators and Heat Pumps

- ***Heat Pumps:*** The objective of a heat pump is to supply heat Q_H into the warmer space
 - For fixed values of Q_L and Q_H can the value of COP_{HP} be lower than unity?

 - What does COP_{HP} represent?

Refrigerators and Heat Pumps

- Performance of refrigerators, air conditioners, and heat pumps:
 - ❑ Most heat pumps have a seasonally averaged COP of 2 to 3
 - ❑ Most existing heat pumps use the cold outside air as the heat source in winter (air-source HP)
 - ❑ In cold climates their efficiency drops considerably when temperatures are below the freezing point
 - ❑ In such cases, geothermal (ground-source) HP that use the ground as the heat source can be used
 - ❑ Such heat pumps are more expensive to install, but they are also more efficient

Refrigerators and Heat Pumps

- Performance of refrigerators, air conditioners, and heat pumps:
 - ❑ Air conditioners are basically refrigerators whose refrigerated space is a room or a building instead of the food compartment
 - ❑ The COP of a refrigerator decreases with decreasing refrigeration temperature
 - ❑ It is not economical to refrigerate to a lower temperature than needed

Refrigerators and Heat Pumps

- Energy efficiency rating (EER): The amount of heat removed from the cooled space in Btu's for 1 W h (watthour) of electricity consumed

$$EER = 3.412 COP_R$$

CLASS ACTIVITY

Class Activity

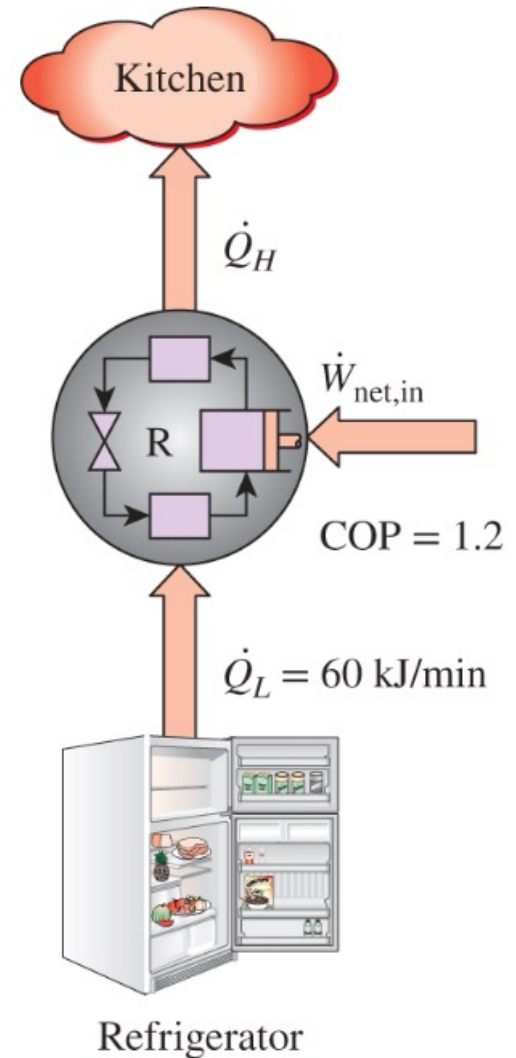
- The household refrigerator with a COP of 1.2 removes heat from the refrigerated space a rate of 60 kJ/min. Determine:
 - a) The electric power consumed by the refrigerator
 - b) The rate of heat transfer to the kitchen air

Class Activity

- Solution:**

$$\dot{W}_{net,in} = \frac{\dot{Q}_L}{COP_R} = \frac{60 \text{ kJ/min}}{1.2} = 50 \frac{\text{kJ}}{\text{min}} = 0.833 \text{ kW}$$

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{net,in} = 60 + 50 = 110 \text{ kJ/min}$$



CLASS ACTIVITY

Class Activity

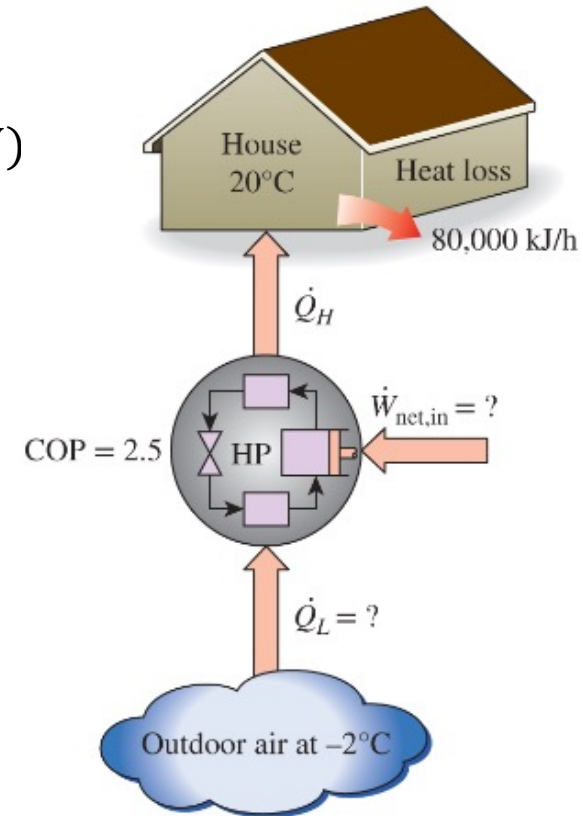
- A heat pump is used to meet the heating requirements of a house and maintain it at $20\text{ }^{\circ}\text{C}$. On a day when the outdoor air temperature drops to $-2\text{ }^{\circ}\text{C}$, the house is estimated to lose heat at a rate of $80,000\text{ kJ/h}$. If the heat pump under these conditions has a COP of 2.5, determine
 - a) The power consumed by heat pump
 - b) The rate at which heat is absorbed from the cold outdoor air

Class Activity

- Solution:**

$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{80,000 \text{ kJ/h}}{2.5} = 32,000 \text{ kJ/h (8.9 kW)}$$

$$\dot{Q}_L = \dot{Q}_L - \dot{W}_{net,in} = (80,000 - 32,000) \frac{\text{kJ}}{\text{h}} = 48,000 \frac{\text{kJ}}{\text{h}}$$



Refrigerators and Heat Pumps

- The Second Law of Thermodynamics: Clausius Statement

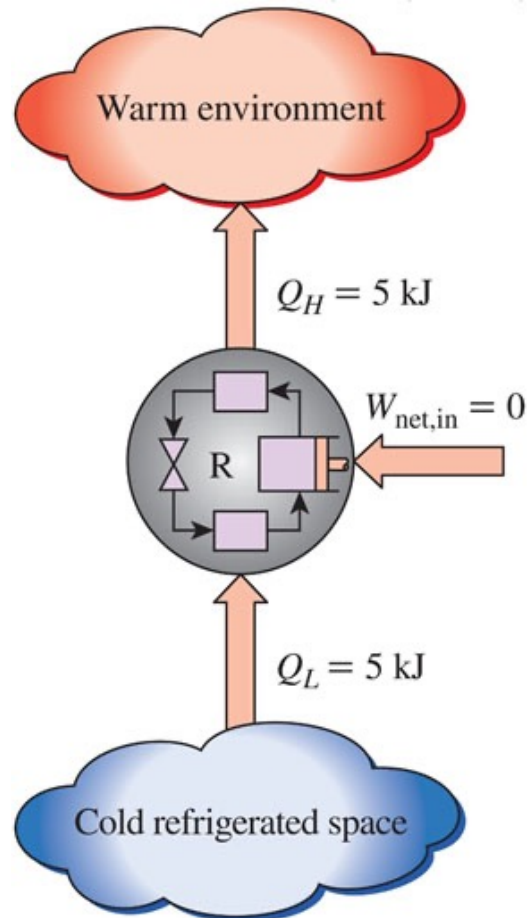
It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

Refrigerators and Heat Pumps

- The Second Law of Thermodynamics: Clausius Statement
 - ❑ It states that a refrigerator cannot operate unless its compressor is driven by an external power source, such as an electric motor
 - ❑ This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one
 - ❑ To date, no experiment has been conducted that contradicts the second law, and this should be taken as sufficient proof of its validity

Refrigerators and Heat Pumps

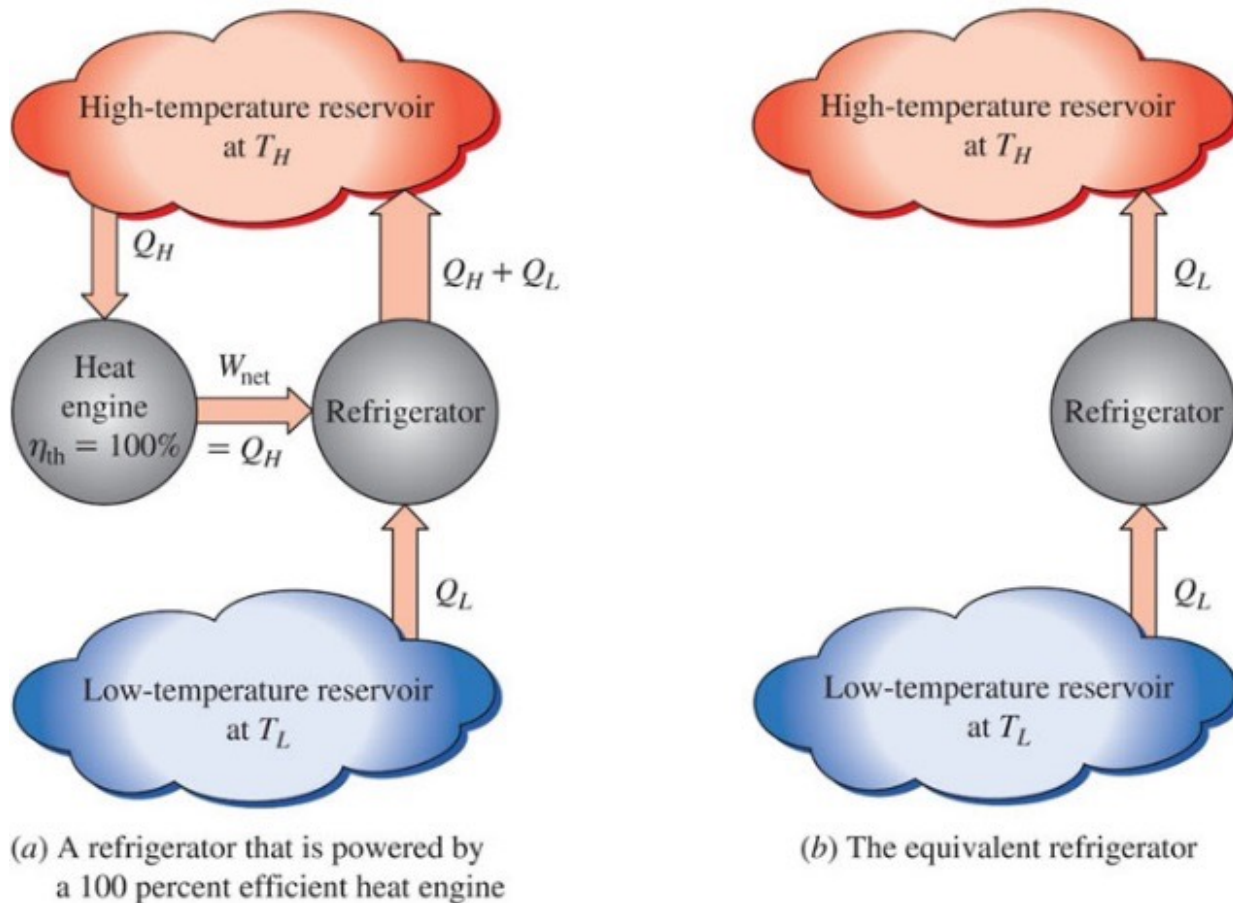
- The Second Law of Thermodynamics: Clausius Statement



A refrigerator that violates the Clausius statement of the second law.

Refrigerators and Heat Pumps

- Equivalence of the Two Statements



Proof that the violation of the Kelvin–Planck statement leads to the violation of the Clausius statement.

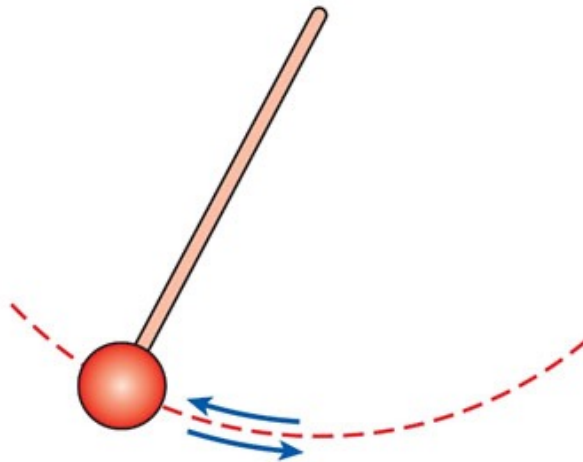
Refrigerators and Heat Pumps

- Equivalence of the Two Statements
 - The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics
 - Any device that violates the Kelvin–Planck statement also violates the Clausius statement, and vice versa

REVERSIBLE AND IRREVERSIBLE PROCESSES

Reversible and Irreversible Processes

- **Reversible process:** A process that can be reversed without leaving any trace on the surroundings
- **Irreversible process:** A process that is not reversible
- All the processes occurring in nature are irreversible



(a) Frictionless pendulum



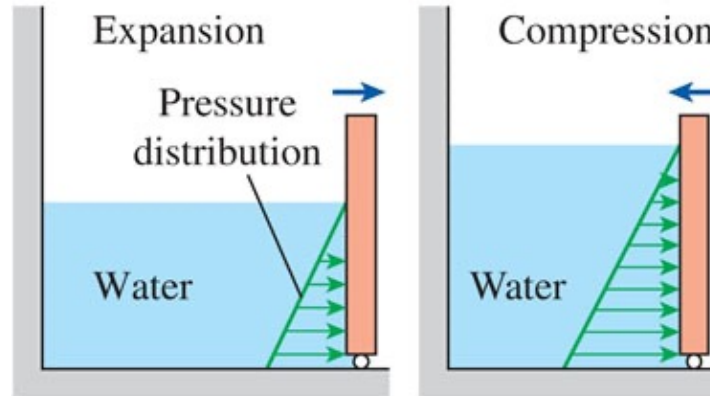
(b) Quasi-equilibrium expansion and compression of a gas

Reversible and Irreversible Processes

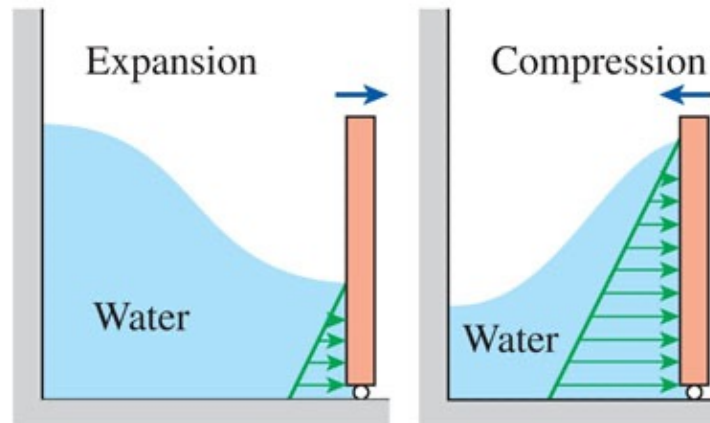
- Why are we interested in reversible processes?
 - 1) They are easy to analyze
 - 2) They serve as idealized models (theoretical limits) to which actual processes can be compared.
- Some processes are more irreversible than others
- We try to approximate reversible processes

Reversible and Irreversible Processes

- Reversible processes deliver the most and consume the least work



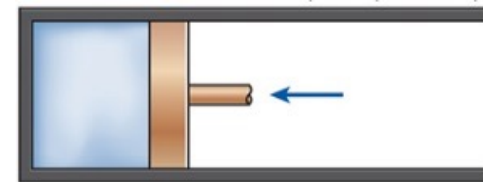
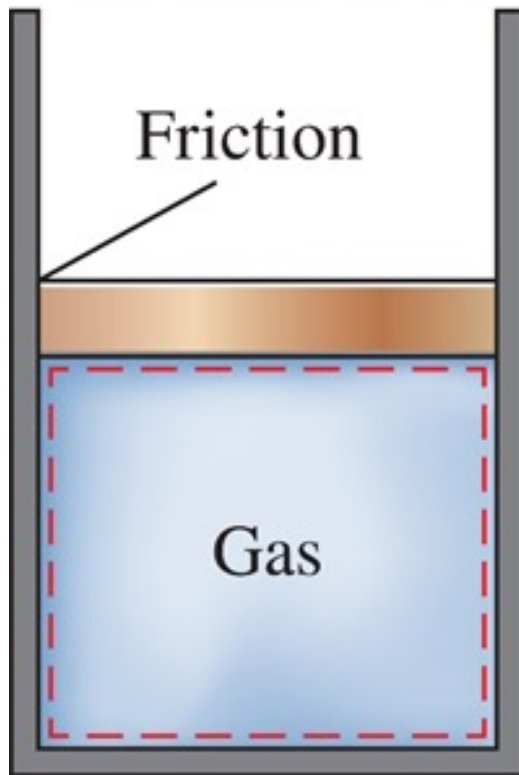
(a) Slow (reversible) process



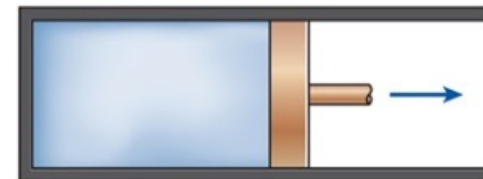
(b) Fast (irreversible) process

Reversible and Irreversible Processes

- The factors that cause a process to be irreversible are called irreversibilities



(a) Fast compression



(b) Fast expansion



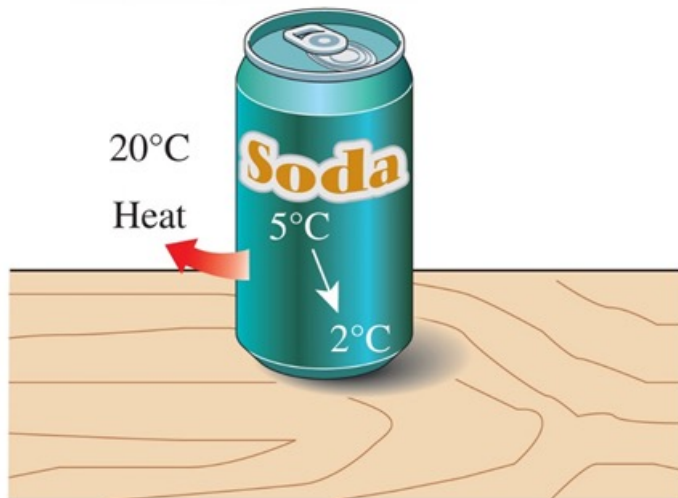
(c) Unrestrained expansion

Reversible and Irreversible Processes

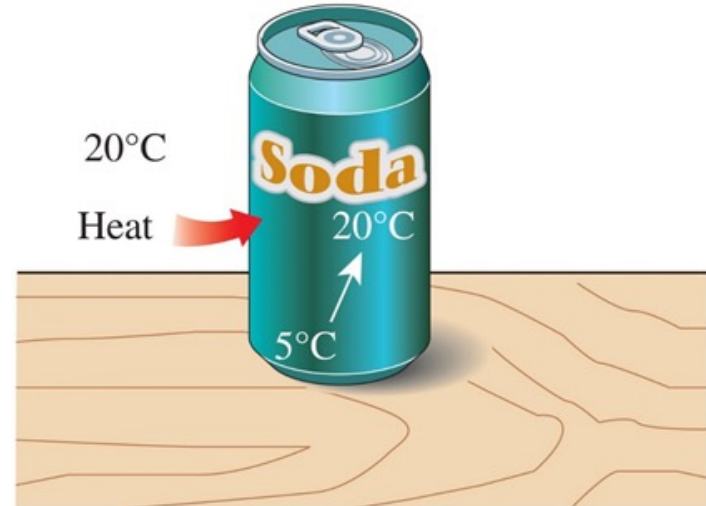
- Irreversibilities includes
 - Friction
 - Unrestrained expansion
 - Mixing of two fluids
 - Heat transfer across a finite temperature difference
 - Electric resistance
 - Inelastic deformation of solids
 - Chemical reactions
- The presence of any of these effects renders a process irreversible

Reversible and Irreversible Processes

- Heat transfer through a temperature difference is irreversible
- The reverse process is impossible



(b) An impossible heat transfer process

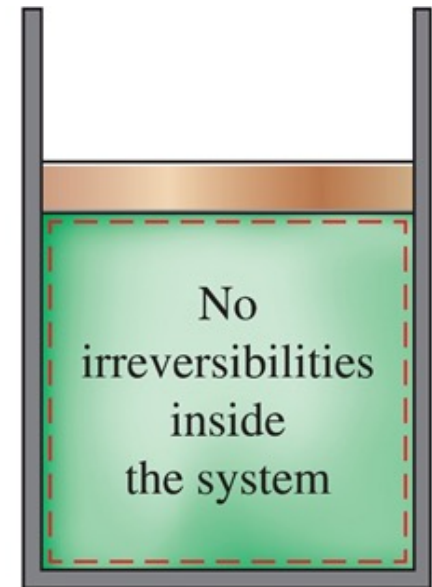


(a) An irreversible heat transfer process

Reversible and Irreversible Processes

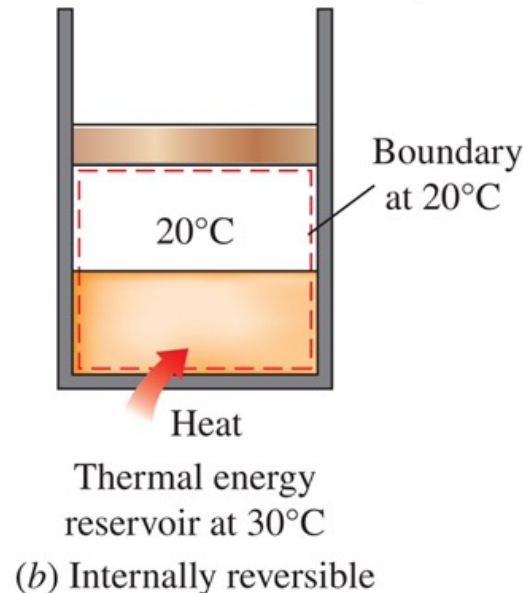
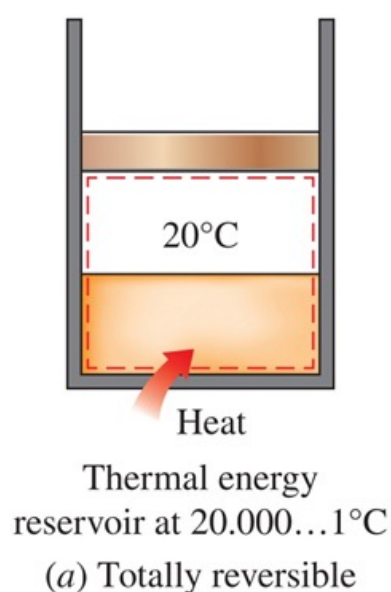
- Internally and Externally Reversible Processes:
 - ❑ **Internally reversible process:** If no irreversibilities occur within the boundaries of the system during the process (e.g., a quasi-equilibrium process)
 - ❑ **Externally reversible:** If no irreversibilities occur outside the system boundaries (e.g., heat transfer between reservoir and a system)

No
irreversibilities
outside
the system



Reversible and Irreversible Processes

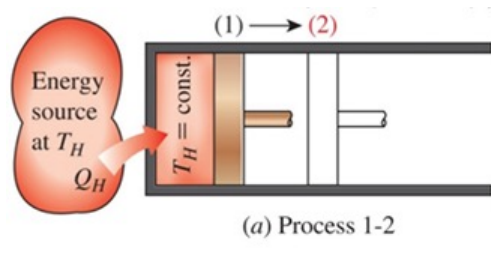
- Internally and Externally Reversible Processes:
 - ❑ Totally reversible process: It involves no irreversibilities within the system or its surroundings
 - ❑ A totally reversible process involves no heat transfer through a finite temperature difference, no nonquasi-equilibrium changes, and no friction or other dissipative effects.



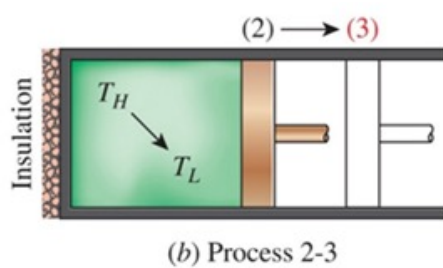
THE CARNOT CYCLE

The Carnot Cycle

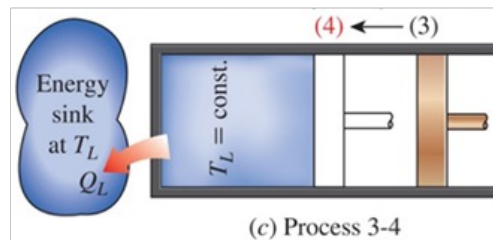
- Execution of the Carnot cycle in a closed system:



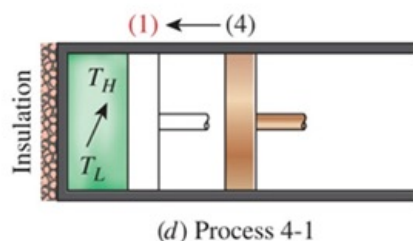
Reversible Isothermal Expansion (process 1-2, $T_H = \text{constant}$)



Reversible Adiabatic Expansion (process 2-3, temperature drops from T_H to T_L)



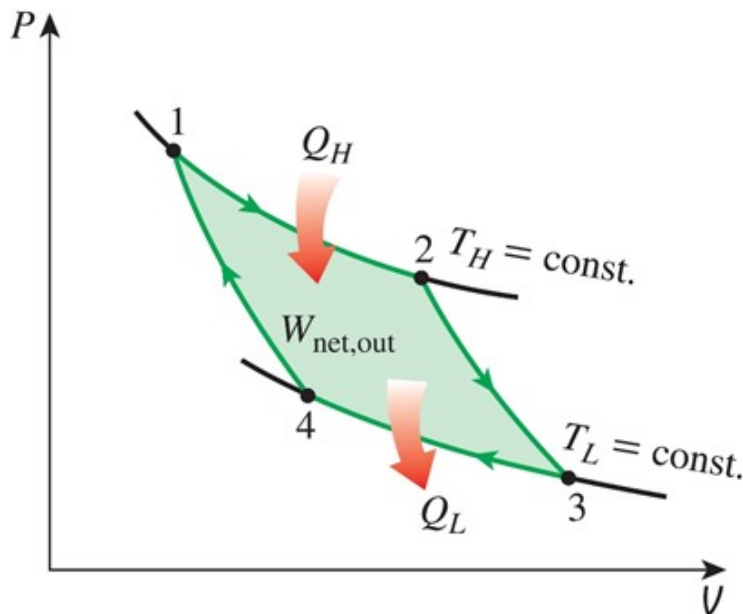
Reversible Isothermal Compression (process 3-4, $T_L = \text{constant}$)



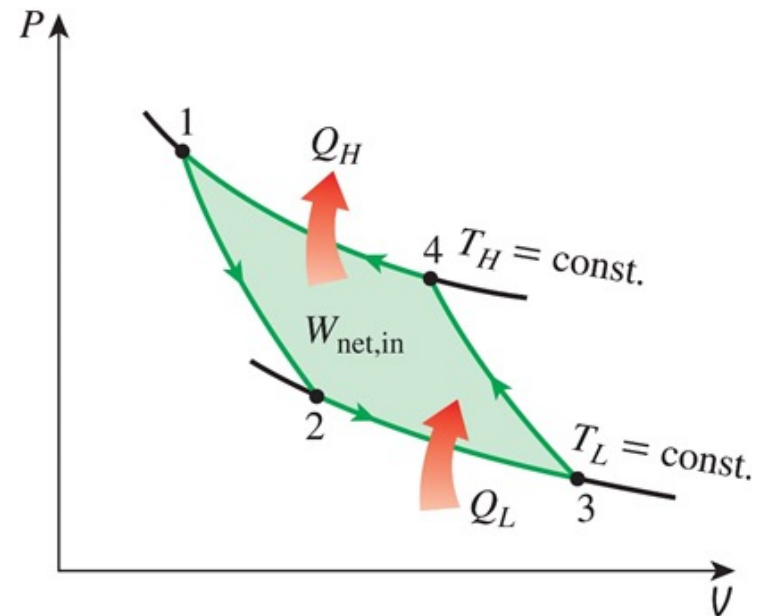
Reversible Adiabatic Compression (process 4-1, temperature rises from T_L to T_H)

The Carnot Cycle

- The Reversed Carnot Cycle
 - The Carnot heat-engine cycle is a totally reversible cycle
 - Therefore, all the processes that comprise it can be reversed, in which case it becomes the Carnot refrigeration cycle



P-V diagram of the Carnot cycle

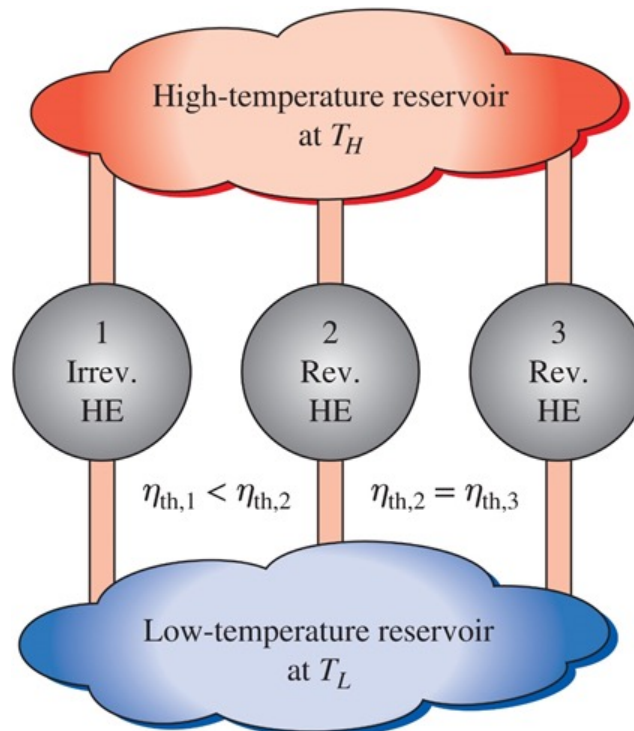


P-V diagram of the reversed Carnot cycle

THE CARNOT PRINCIPLES

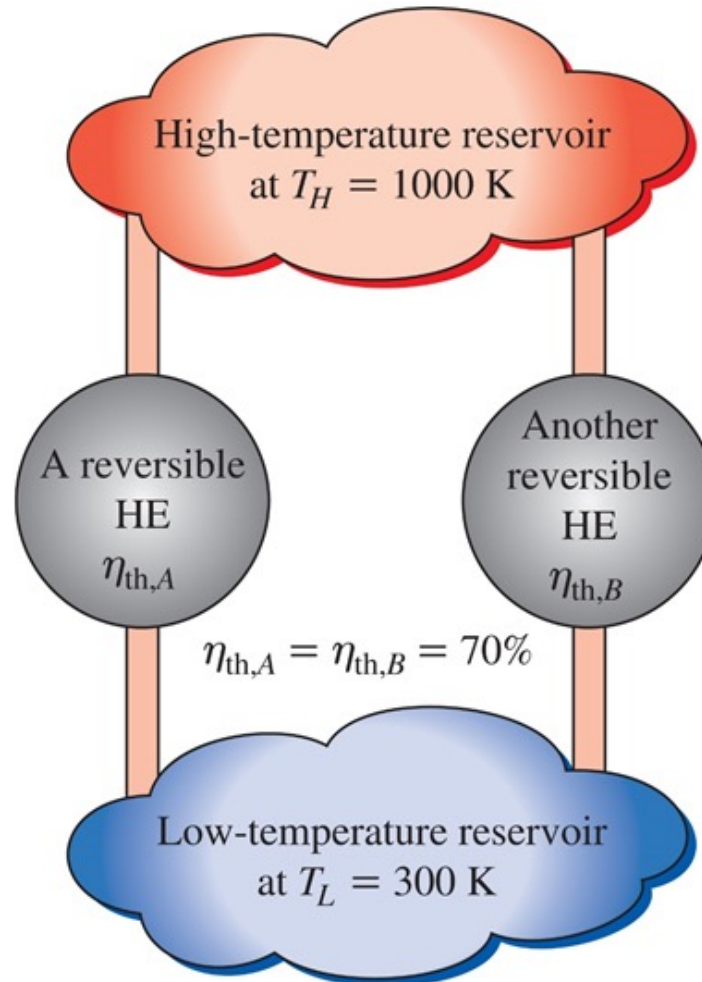
The Carnot Principles

- Two main principles:
 1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs
 2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same



The Carnot Principles

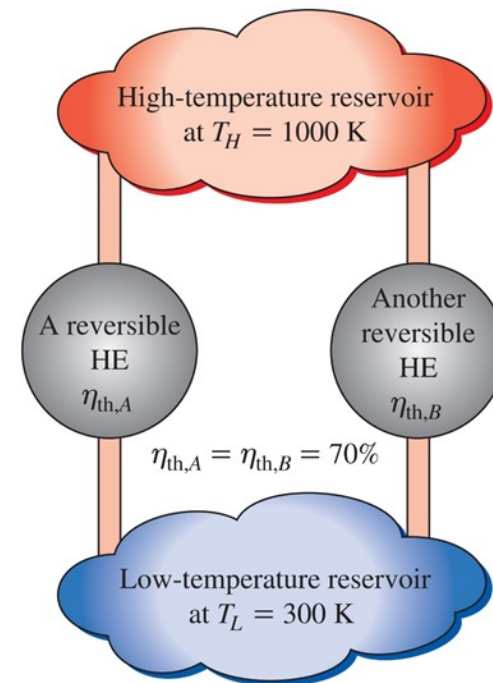
- All reversible heat engines operating between the same two reservoirs have the same efficiency (the second Carnot principle)



THE THERMODYNAMIC TEMPERATURE SCALE

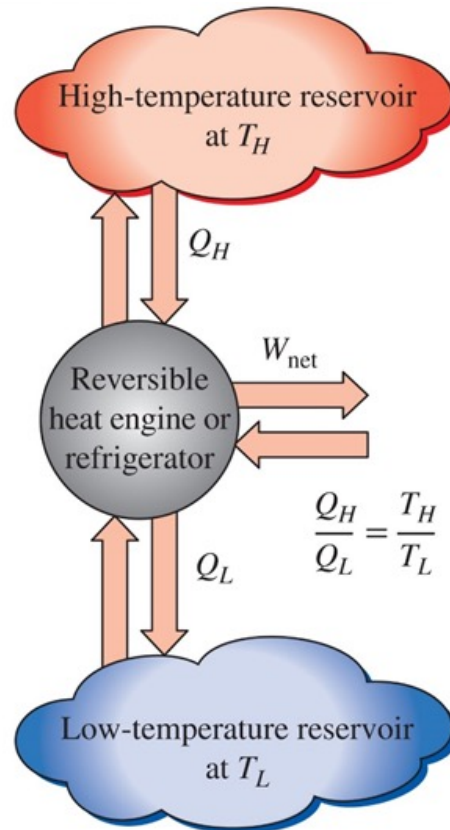
The Thermodynamic Temperature Scale

- A temperature scale that is independent of the properties of the substances that are used to measure temperature is called a thermodynamic temperature scale
- Such a temperature scale offers great conveniences in thermodynamic calculations



The Thermodynamic Temperature Scale

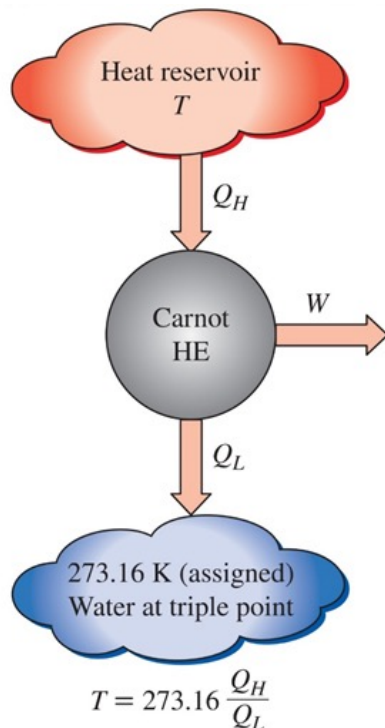
- This temperature scale is called the Kelvin scale, and the temperatures on this scale are called absolute temperatures
 - For reversible cycles, the heat transfer ratio Q_H/Q_L can be replaced by the absolute temperature ratio T_H/T_L



$$\left(\frac{Q_H}{Q_L}\right)_{rev} = \frac{T_H}{T_L}$$

The Thermodynamic Temperature Scale

- This temperature scale is called the Kelvin scale, and the temperatures on this scale are called absolute temperatures
 - A conceptual experimental setup to determine thermodynamic temperatures on the Kelvin scale by measuring heat transfers Q_H and Q_L .

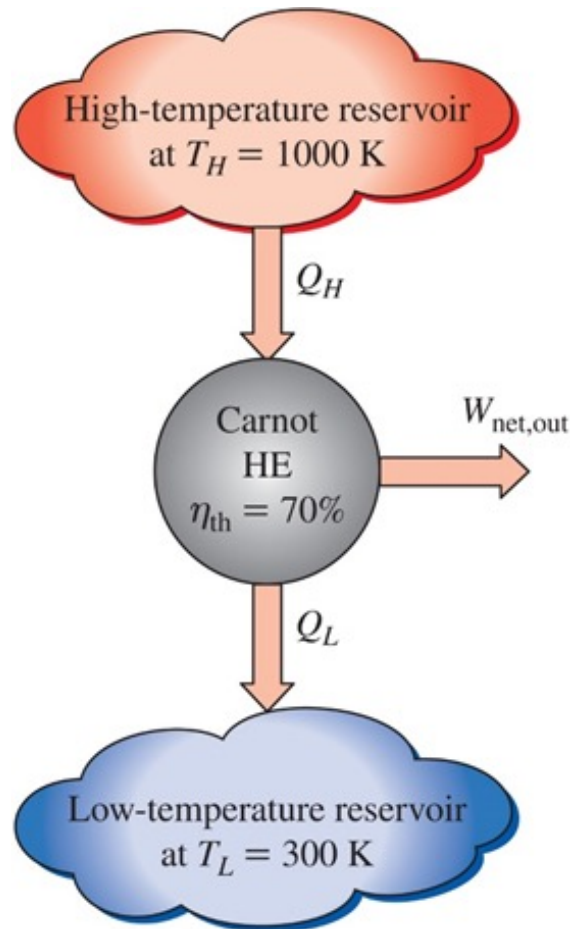


$$T = 273.16 \frac{Q_H}{Q_L}$$

THE CARNOT HEAT ENGINE

The Carnot Heat Engine

- The Carnot heat engine is the most efficient of all heat engines operating between the same high- and low-temperature reservoirs



The Carnot Heat Engine

- Any heat engine:

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

- Any Carnot heat engine:

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

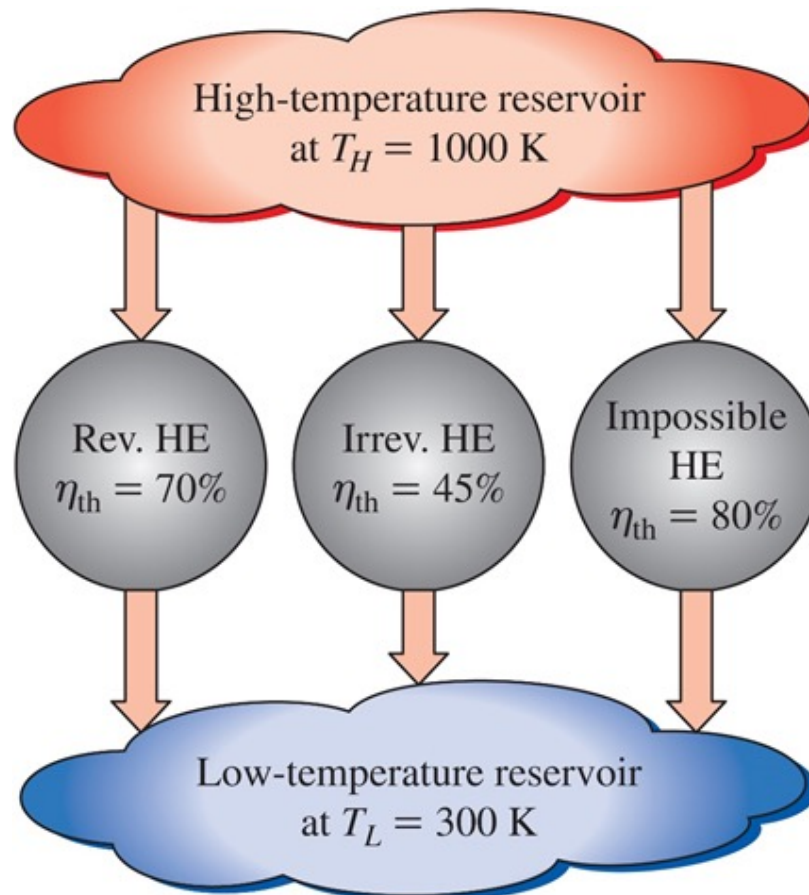
The Carnot Heat Engine

- We can say:

$$\eta_{th} = \begin{cases} < \eta_{th,rev} & \text{irreversible heat engine} \\ = \eta_{th,rev} & \text{reversible heat engine} \\ > \eta_{th,rev} & \text{impossible heat engine} \end{cases}$$

The Carnot Heat Engine

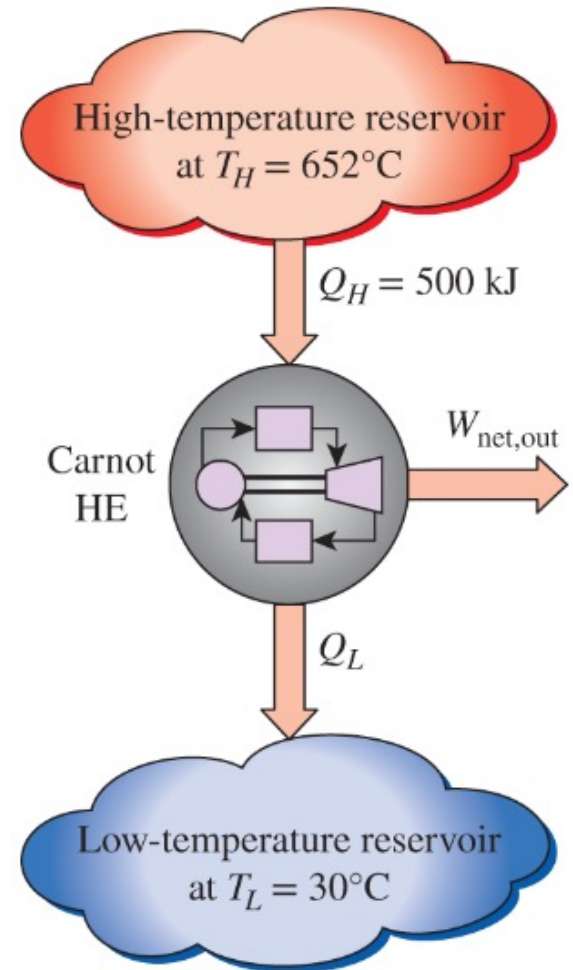
- No heat engine can have a higher efficiency than a reversible heat engine operating between the same high- and low-temperature reservoirs



CLASS ACTIVITY

Class Activity

- A Carnot heat engine receives 500 kJ of heat per cycle from a high-temperature source at 652 °C and rejects heat to a low-temperature sink at 30 °C. Determine:
 - a) A thermal efficiency of this Carnot engine
 - b) The amount of heat rejected to the sink per cycle



Class Activity

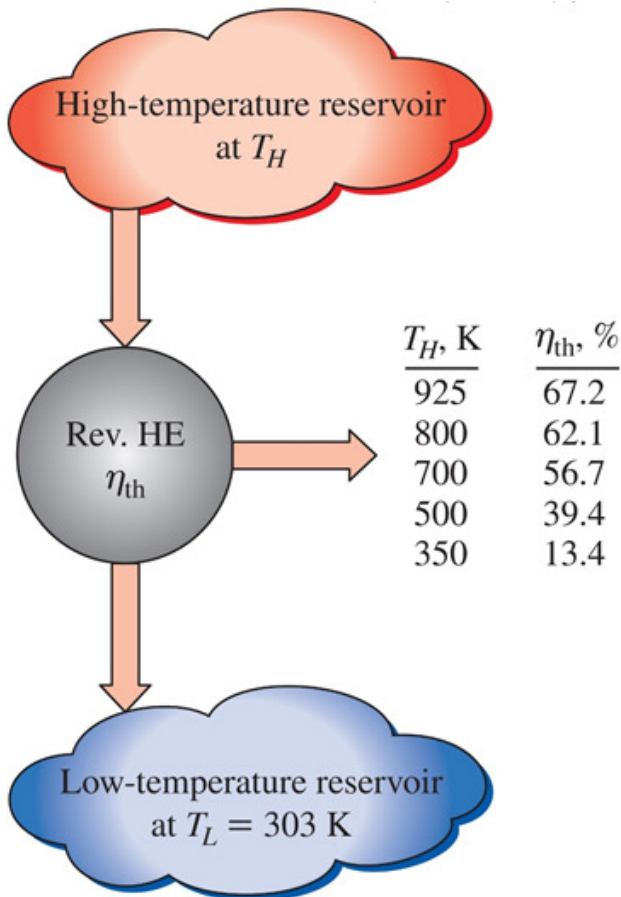
- Solution:

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H} = 1 - \frac{30 + 273}{652 + 273} = 0.672$$

$$Q_{L,rev} = \frac{T_L}{T_H} Q_{H,rev} = \frac{30 + 273}{652 + 273} (500 \text{ kJ}) = 164 \text{ kJ}$$

The Carnot Heat Engine

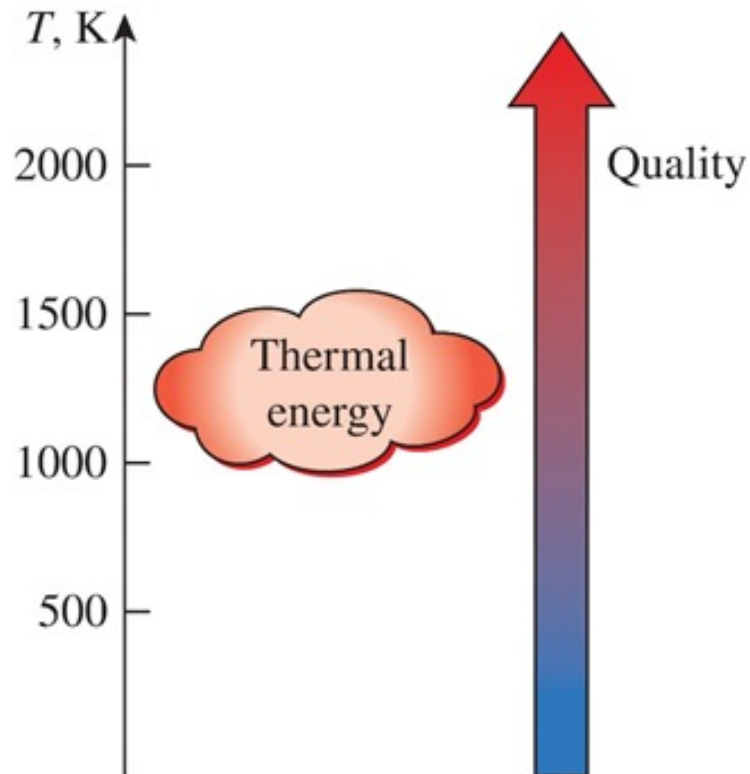
- The quality of Energy: The fraction of heat that can be converted to work as a function of source temperature (for $T_L = 303$ K).



$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

The Carnot Heat Engine

- The higher the temperature of the thermal energy, the higher its quality



THE CARNOT REFRIGERATOR AND HEAT PUMP

The Carnot Refrigerator and Heat Pump

- For any refrigerator or heat pump:

$$COP_R = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

$$COP_{HP} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

The Carnot Refrigerator and Heat Pump

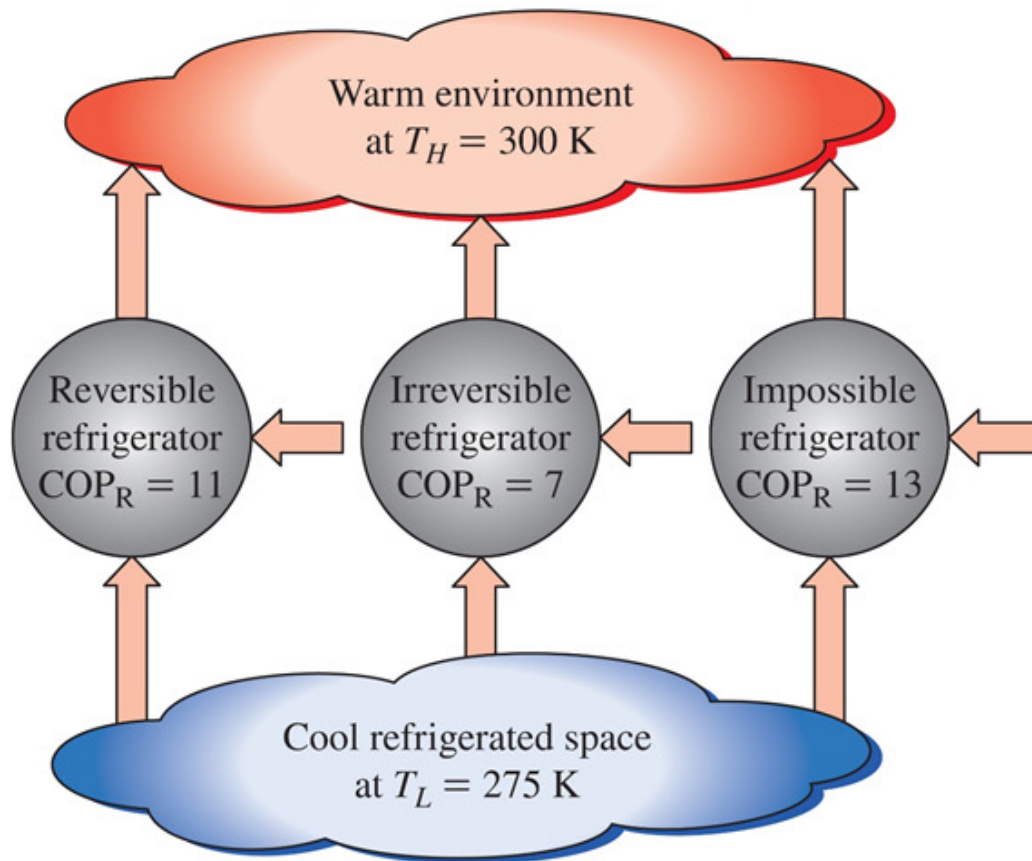
- For any refrigerator or heat pump:

$$COP_{R,rev} = \frac{1}{\frac{T_H}{T_L} - 1}$$

$$COP_{HP,rev} = \frac{1}{1 - \frac{T_L}{T_H}}$$

The Carnot Refrigerator and Heat Pump

- No refrigerator can have a higher COP than a reversible refrigerator operating between the same temperature limits.



The Carnot Refrigerator and Heat Pump

- The COP of a reversible refrigerator or heat pump is the maximum theoretical value for the specified temperature limits
- Actual refrigerators or heat pumps may approach these values as their designs are improved, but they can never reach them

$$COP_R = \begin{cases} < COP_{R,rev} & \textit{irreversible refrigerator} \\ = COP_{R,rev} & \textit{reversible refrigerator} \\ > COP_{R,rev} & \textit{impossible refrigerator} \end{cases}$$

The Carnot Refrigerator and Heat Pump

- The COPs of both the refrigerators and the heat pumps decrease as T_L decreases
- That is, it requires more work to absorb heat from lower-temperature media.

$$COP_R = \begin{cases} < COP_{R,rev} & \text{irreversible refrigerator} \\ = COP_{R,rev} & \text{reversible refrigerator} \\ > COP_{R,rev} & \text{impossible refrigerator} \end{cases}$$

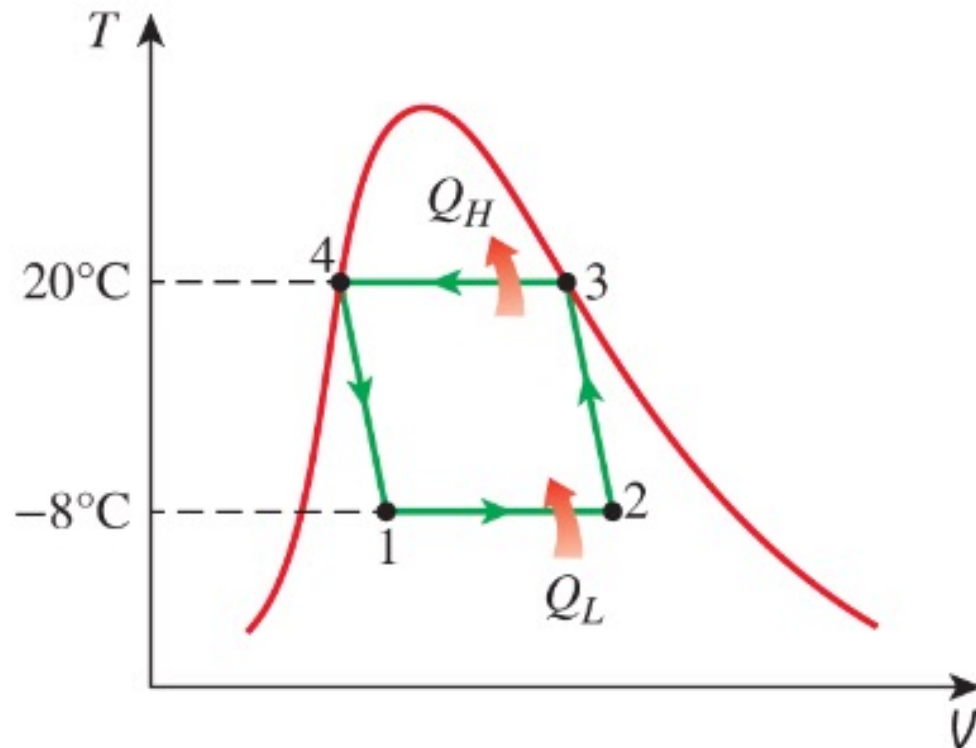
CLASS ACTIVITY

Class Activity

- A Carnot refrigeration cycle is executed in a closed system in the saturated liquid-vapor mixture region using 0.8 kg of refrigerant 134-a as the working fluid. The maximum and the minimum temperatures in the cycle are 20 and $-8\text{ }^{\circ}\text{C}$, respectively. It is known that the refrigerant is saturated at the end of the heat rejection process, and the net work input to the cycle is 15 kJ. Determine the fraction of the mass of the refrigerant that vaporizes during the heat addition process and the pressure at the end of the rejection process.

Class Activity

- Solution:



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$$COP_R = \frac{1}{\frac{T_H}{T_L} - 1} = \frac{1}{\frac{20 + 273}{-8 + 273} - 1} = 9.464$$

$$Q_L = COP_R \times W_{in} = (9.464)(15 \text{ kJ}) = 142 \text{ kJ} \quad (\text{The amount of cooling})$$

$$Q_l = m_{eva} h_{fg @ -8^\circ\text{C}} = \frac{142 \text{ kJ}}{204.59 \frac{\text{kJ}}{\text{kg}}} = 0.694 \text{ kg} \quad (\text{Table A - 11})$$

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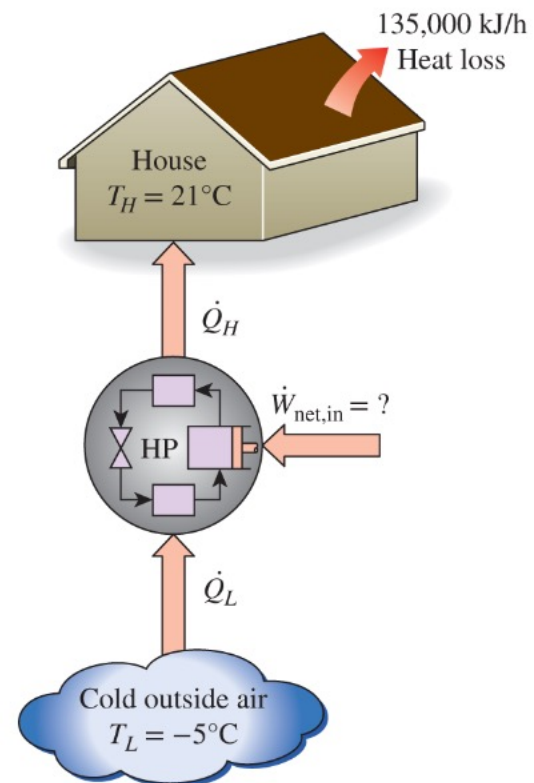
- Solution:

$$\text{Mass Fraction} = \frac{m_{evap}}{m_{total}} = \frac{0.694 \text{ kg}}{0.8 \text{ kg}} = 0.868$$

$$P_4 = P_{sat @ 20^\circ\text{C}} = 572.1 \text{ kPa}$$

Class Activity

- A heat pump is to be used during the winter. The house is to be maintained at $21\text{ }^{\circ}\text{C}$ at all times. The house is estimated to be losing heat at a rate of $135,000\text{ kJ/h}$ when the outside temperature drops to $-5\text{ }^{\circ}\text{C}$. Determine the minimum power required to drive this heat pump.



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- Solution:

$$COP_{HP,rev} = \frac{1}{1 - T_L/T_H} = \frac{1}{1 - \frac{-5 + 273}{21 + 273}} = 11.3$$

$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{37.5 \text{ kW}}{11.3} = 3.32 \text{ kW}$$

